AD-A100 552 FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER ATL--ETC F/G 17/7
LORAN-C IN MOUNTAINOUS AREAS. PHASE I. VERMONT TESTS.(U)
APR 81 L RZONCA
UNCLASSIFIED FAA-CT-81-22 FAA-RD-81-24 NL

1 of 1
AD A
100552

END
DATE
FILMED
7-81
DTIC

Report No. FAA-RD-81-24
FAA-CT-81-22

AD A100552

LORAN-C IN MOUNTAINOUS AREAS, PHASE 1: VERMOUNT TESTS

Lorraine Rzonca

FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER
Atlantic City Airport, N.J. 08405

DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

INTERIM REPORT

JUNE 1981

Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D. C. 20590

Technical Report Documentation Page

1. Report No. FAA-RD-81-24	2. Government Accession No. AD-A100552	3. Recipient's Catalog No.
4. Title and Subtitle LORAN-C IN MOUNTAINOUS AREAS, PHASE I: VERMONT TESTS		5. Report Date Apr[redacted]1981
		6. Performing Organization Code
7. Author's) Lorraine Rzonca		8. Performing Organization Report No. FAA-CT-81-22
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 048-312-520
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590		13. Type of Report and Period Covered Interim Report September 1979-March 1980
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Flight tests were conducted in the State of Vermont to determine the suitability of long range navigation (LORAN)-C for airborne area navigation (RNAV) operations in mountainous areas. A production receiver, the Teledyne TDL-711, and a ground-based multi-distance measuring equipment (DME) reference system were used to obtain accuracy statistics during en route flights and nonprecision approaches to four airports.

The Federal Aviation Administration (FAA) accuracy criteria (Advisory Circular AC 90-45A) were met for both nonprecision approaches and en route flights when the primary triad (Seneca, Caribou, Nantucket) was used and when no automatic triad switches occurred during the flight.

The mean value of the LORAN-C grid bias for the primary triad was generally 0.1 nautical miles (nmi) or less at each of the four airports; however, the bias for the alternate triad (Seneca, Nantucket, Carolina Beach) was significant (1.9 nmi north and 0.5 nmi east at Burlington Airport).

17. Key Words LORAN-C Area Navigation (RNAV) Airborne LORAN-C Error Statistics	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	20	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

GENERAL.

The Long Range Navigation (LORAN)-C System has been used for navigation and for specialized military air operations since the late 1950's. However, serious application to civil air navigation is a relatively recent phenomenon. Technological advances which decrease LORAN-C equipment costs and the commissioning of several new LORAN-C chains which increase domestic United States (U.S.) coverage have stimulated interest in the potential of LORAN-C as a navigational aid (NAVAID) for general aviation.

This project reflects the increased interest within the civil aviation community. It is part of an overall program within the Federal Aviation Administration (FAA) to collect data in support of a 1982 decision to recommend the civil radio navigation system of the future.

LORAN-C CHARACTERISTICS.

LORAN-C is a pulsed, low frequency (100 kilohertz (kHz)) radio navigation system. The difference in time of arrival of signals from two transmitters corresponds to a hyperbolic line-of-position (LOP) on the earth's surface. The time difference associated with a second pair of transmitters forms another LOP. The intersection of the two LOP's defines the position of the LORAN-C receiver.

Transmitters are grouped according to chains consisting of a master station and from two to four secondary stations. Each chain is characterized by its group repetition interval (GRI) which is the length of the transmission period during which the master station and each secondary, in turn, emits its coded pulse group at precisely controlled times. Since the low radio frequency used by LORAN-C provides for ground-wave propagation and coverage that is not limited by line-of-sight between transmitter and receiver, LORAN-C is a likely candidate for aircraft area navigation (RNAV) at airports located in mountainous terrain. Unfortunately, topographic features (deviations from a smooth spherical earth) in combination with nonuniform conductivity cause anomalies in the navigation grid (latitude/longitude values) predicted for a smooth, spherical, homogeneous earth. These terrain-caused position anomalies, coupled with the temporal grid warpage due to propagation anomalies, produce an irregular pattern for the navigation grid. Theoretical calculations (reference 1) show that grid warpage due to rough terrain decreases with increasing altitude. Therefore, the capability of a LORAN-C airborne navigation set to satisfy the FAA Advisory Circular (AC) 90-45A requirements vary with geographic location and aircraft altitude, as well as with position uncertainty caused by the inherent characteristics of a hyperbolic navigation system.

FLIGHT TEST OBJECTIVES.

The overall goal of this project is to determine the suitability of LORAN-C for airborne RNAV operations in mountainous areas. Existing production airborne LORAN-C equipment will be evaluated during en route, terminal, and non-precision approach procedures. Accuracy measurements, with respect to a ground-based position reference system, will be analyzed for compliance with requirements established by AC 90-45A.

Specific objectives for Phase I (Vermont tests) were:

1. To collect approximately 32 hours of flight data in Vermont (approaches to five designated airports and en route flights) in support of the

Transportation Systems Center (TSC) LORAN-C program (reference 2).

2. To compare accuracy statistics of flight data with AC 90-45A requirements for 2-D RNAV systems.

3. To compare accuracy statistics of primary and alternate triads of the Northeast U.S. Chain.

4. To compare results from medium and low altitude en route flights.

5. To make a comparative evaluation of the TDL-711 Micro-Navigator, and the TDL-424 (more expensive military system), both developed by the Teledyne Systems Company.

6. To generate a data base consisting of the time differences (TD's) measured by the airborne LORAN-C and of the corresponding reference position (latitude/longitude) for subsequent use in verification of performance of a LORAN-C simulator.

BACKGROUND.

During summer 1979, an FAA contractor (Systems Control, Inc.) conducted nonprecision approaches at several mountainous airports in the Western U.S. (reference 3). The position reference for these tests was the Remote Area Precision Positioning System (RAPPS) developed by the Sierra Nevada Corporation under a Systems Research and Development Service (SRDS) contract. Technical details of the multiple distance measurement equipment (DME) RAPPS are included in reference 4. In late summer, RAPPS was delivered to the FAA Technical Center for validation and use in Vermont LORAN-C tests.

In early September 1979, the accuracy of the RAPPS was validated at the FAA Technical Center against the Nike/Hercules Tracking Radar System. With DME range biases removed, RAPPS showed a mean error of 345 feet and a 1-sigma range error of 256 feet for a four-DME station solution. With range biases retained, the 1-sigma range error was 307 feet. Details of the accuracy analysis and discussion of the error budget of the tracking radar are included in reference 5.

Between September 1979 and March 1980, operational evaluations of RAPPS (both hardware and software) were performed at the FAA Technical Center and at field sites in Vermont. Results of these tests are discussed in reference 6. Concurrently, LORAN-C accuracy data (RAPPS reference) were collected in support of the TSC Vermont program.

DISCUSSION

DESCRIPTION OF TEST BED.

The Vermont flights were made in the FAA Technical Center Convair CV-580, a twin-engine turboprop aircraft. The airborne equipment consisted of two LORAN-C navigators (TDL-711 and TDL-424) and the RAPPS data acquisition and position reference system.

EQUIPMENT. The TDL-711 was supplied by TSC for the Vermont tests (detailed characteristics are provided in table 1). The TDL-424 (AN/ARN-133) is a more sophisticated unit. Details are included in table 2. Both LORAN-C units are equipped with an "area calibration" feature which forces the LORAN-C computed position coordinates to coincide with surveyed coordinates if discrepancies caused by propagation anomalies are observed. The RAPPS data acquisition and position reference system is shown in the block diagram of figure 1; technical details of this system are provided in reference 4. RAPPS consists of three subsystems: LORAN-C/clock/altimeter equipment, DME tracker, and data coordinator/recorder/display units.

TABLE 1. TDL-711 LORAN-C MICRO-NAVIGATOR CHARACTERISTICS

NAVIGATION SYSTEM	
Mode	Great Circle
Grid Reference (operator selected)	Lat/Long (0.1 min) Time Difference (0.1 μs)
North Reference	True or Magnetic
Waypoints	9 (nonvolatile)
Display Resolution	
Distance/Bearing to Waypoint	0.1 nmi/1°
Estimated Time En Route/ Ground Speed	0.1 min/1 kt
Crosstrack Distance/ Desired Track	0.01 nmi/1°
Track-Angle Error/Ground Track	1°/1°
Offset (input) Magnetic	0.01 nmi/1°
Repeatable Accuracy	Better than 0.1 nmi
Left-right Steering to CDI	1.25 nmi full scale
LORAN-C DATA	
Area of Operation	Two LORAN-C Triads
General	Exceed RTCA DO-159 Type III Requirements
Acquisition	Automatic
Velocity Envelope (unaided)	0 to 950 kt
Master Independent	Automatic
ENVIRONMENTAL	
Operating Temperature	-55° to 55° C
Altitude (unpressurized)	20,000 feet
Power	18-32 Vdc, less than 40 watts
PHYSICAL	
Receiver Computer Unit	7.62H x 7.50W x 12.58D in., 11.0 lb
Control Display Unit	4.50 x 5.75W x 6.50D in., 4.5 lb
Antenna	16.5H x 2.5W x 10.0D in., 0.5 lb

TABLE 2. TDL-424 LORAN-C CHARACTERISTICS

NAVIGATION SYSTEM	
Mode - Long Range	Great Circle
- Short Range (less than 10 nmi)	Flat Earth
Grid Reference (operator selected)	Lat/Long (0.01 min) Time Difference (10 ns)
North Reference	True or Magnetic
Waypoints (manual or automatic)	9
Displays Resolution	
Range/Bearing	0.1 nmi/1.0°
Ground Track/Ground Speed	1.0°/1.0 kt
Desired Track/Track-Angle Error	1.0°/0.1°
Time to Waypoint/Distance Crosstrack	0.1 min/0.01 nmi
Left-right Steering to CDI	1/2 nmi full-scale
Overall Accuracy	50 to 700 feet
LORAN DATA	
LORAN Chains	11 Permanent
Stations Tracked	5
General Performance	Exceeds DO-159 Type III Requirements
Acquisition	Automatic
Minimum Signal-to-Noise Ratio	Acquisition - 14 dB Tracking - 26 dB
Velocity Envelope (unaided)	0 to 1,600 fps
Master Independent	Automatic
ENVIRONMENTAL	
Operating Temperature/Altitude	DO-160 (B-1)
Power	28 Vdc; 3 amps max.
Reliability	1,000 hr MTBF
PHYSICAL	
Receiver Computer Display Unit	9.0H x 5.75W x 6.5D in., 9.0 lb
Antenna Coupler	4.2H x 3.75W x 7.0D in., 20 lb
Antenna	2.0H x 3.0W x 15.0D in., 1.5 lb

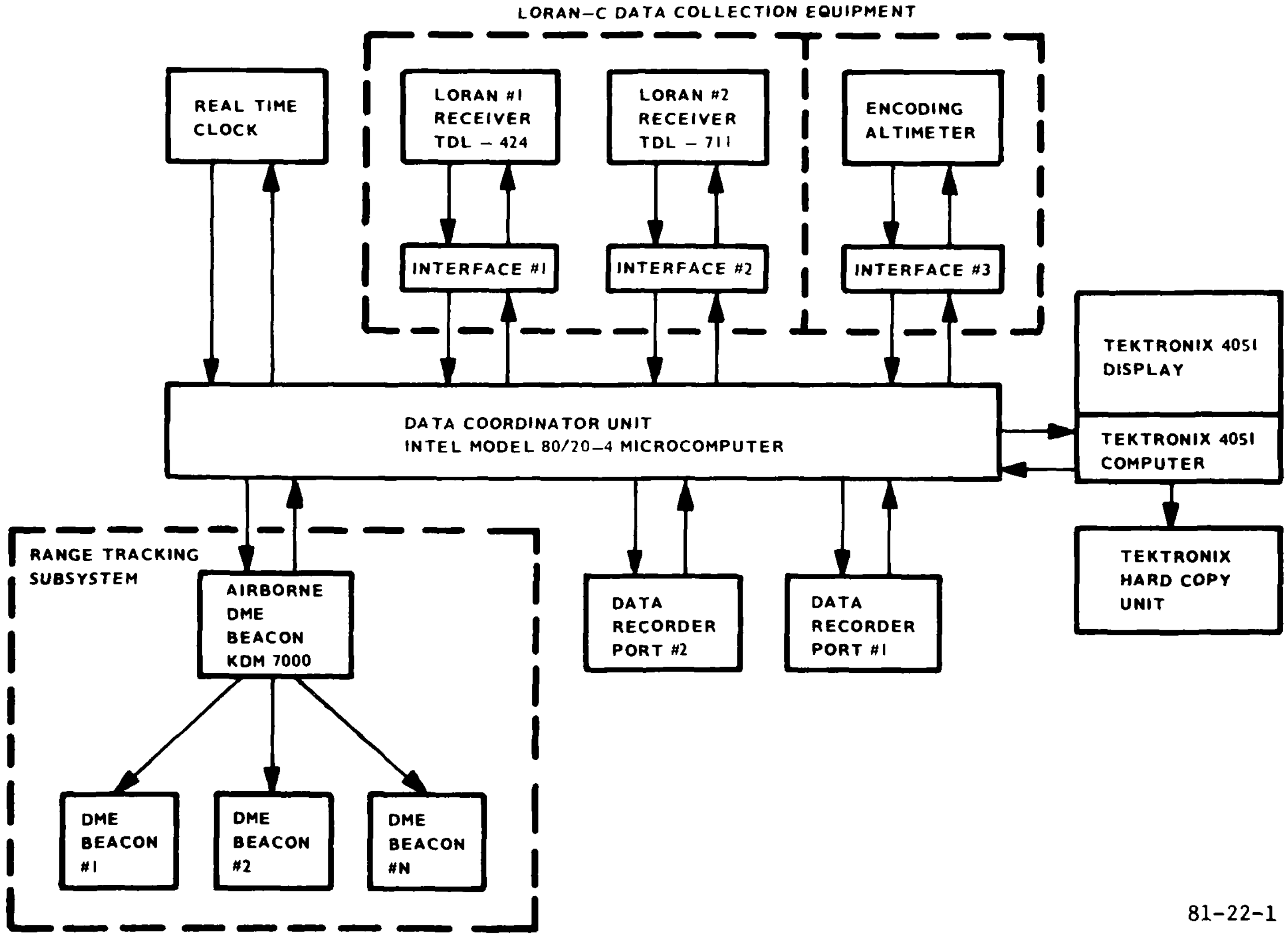

FIGURE 1. DIAGRAM OF REMOTE AREA PRECISION POSITIONING SYSTEM (RAPPS)

For the Vermont tests, the tracker subsystem consisted of a standard airline DME interrogator (King Radio Corporation model KDM-7000) in the CV-580, together with three standard ground station DME beacons (Butler National Corporation model 1020 with 200-nautical mile range (nmi) range, a model 1020 with 80-nmi range, and a model 1066 with 80-nmi range) and four small beacons (Vega 316-L with 40-nmi range). The Butler DME's were installed on mountain tops to provide en route coverage, as well as coverage at some airports, while the Vega DME's were temporarily installed in the vicinity of each airport when tests were to be conducted.

Range measurements from the ground beacons (one range measurement per second, cycled through a total of six DME's) were included on the flight data recording with TDL-424 latitude/longitude, TDL-711 data from the control display unit and the receiver computer unit, altitude data, and clock time. Data were stored on 9-track tape for subsequent analysis. Real-time track plots of LORAN-C and DME-derived positions were displayed on the Tektronix 4051 for inflight quick-look purposes. The locations of the two LORAN-C antennas, the airborne DME antenna, and the RAPPS avionics rack in the CV-580 are sketched in figure 2.

TEST AREA. The test sites included the airspace around and between the five Vermont airports of Burlington (BTV), Barre-Montpelier (MPV), Morrisville (MVL), Newport (EFK), and Rutland (RUT). The locations of four of the five test airports (Rutland excluded) and the three Butler DME sites are shown in figure 3. En route patterns which were flown are shown in figures 4 and 5. Approach plates for the test airports were based on RNAV instrument approach procedures developed by the FAA upon request by the State of Vermont. They were based upon existing requirements of AC 90-45A and the FAA Terminal Instrument Procedures (TERPS) Handbook and were restricted to VFR conditions only (pending certification of the LORAN-C equipment).

The Vermont test area was located within the coverage area of the Northeast U.S. LORAN-C Chain (GRI 9960) as shown in figure 6. The primary LORAN-C triad for these tests consisted of Seneca, New York (N.Y.), Caribou, Maine (Me.), and Nantucket, Massachusetts (Mass.). The alternate triad was Seneca, N.Y., Nantucket, Mass., and Carolina Beach, North Carolina (N.C.).

DATA COLLECTION AND PROCESSING.

LORAN-C and DME range information were collected on the RAPPS during those en route flights and nonprecision approaches listed in the test profile in table 3.

The computer program which processes the RAPPS data:

1. Reads the information contained between specified start/stop times.

2. Computes a least squares fitted range from four consecutive range values derived from each DME.

3. Computes an aircraft position (with respect to an arbitrary local coordinate system) from the fitted ranges.

4. Converts the TDL-711 and TDL-424 latitude/longitude values to the local coordinate system.

5. Computes error statistics of TDL-711 and TDL-424 as compared to RAPPS position.

6. Prints required LORAN-C parameters from the TDL-711 receiver processor unit, DME ranges, and error statistics for TDL-711 and TDL-424.

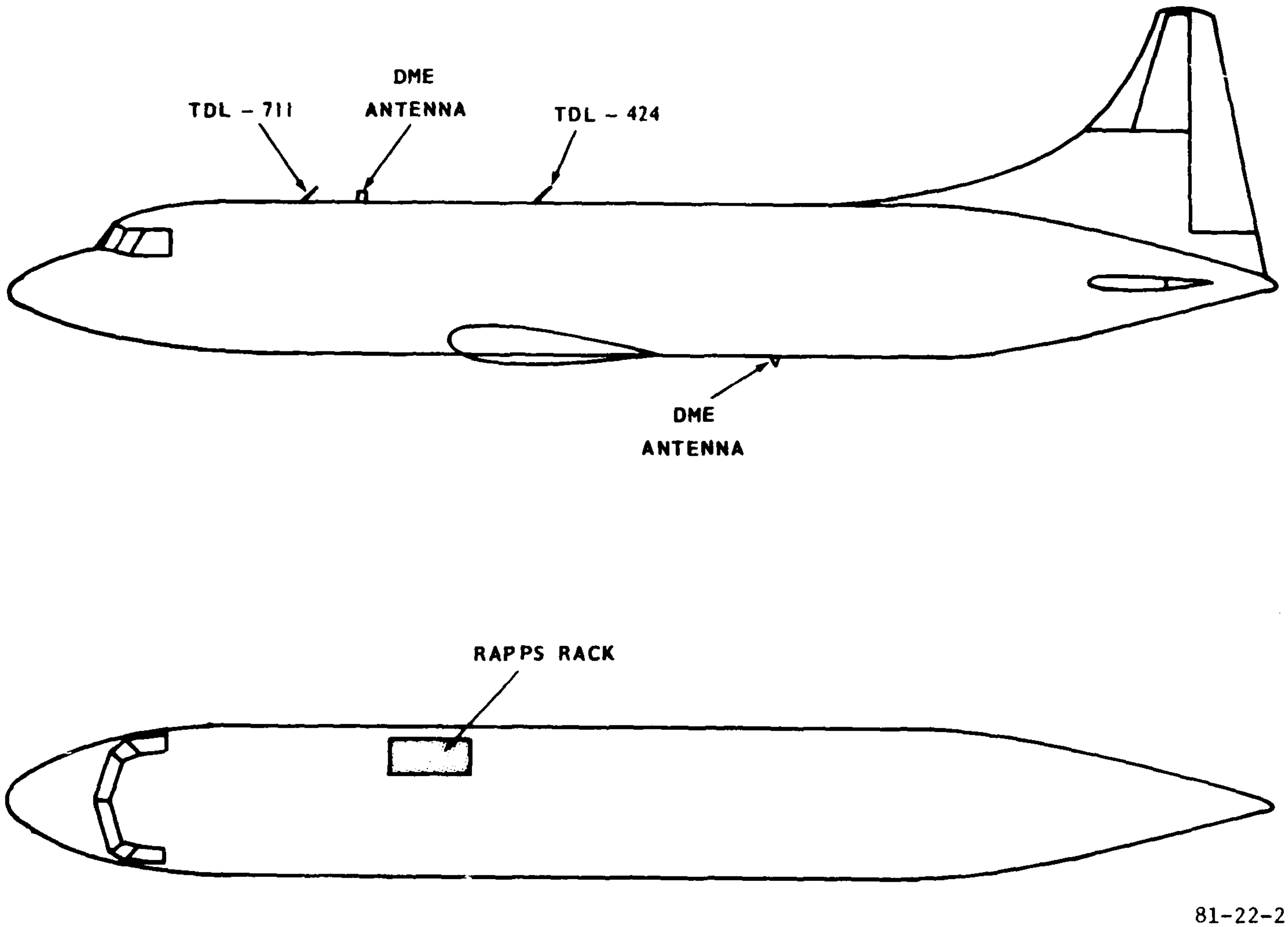

FIGURE 2. ANTENNAS AND RAPPS RACK IN CV-580

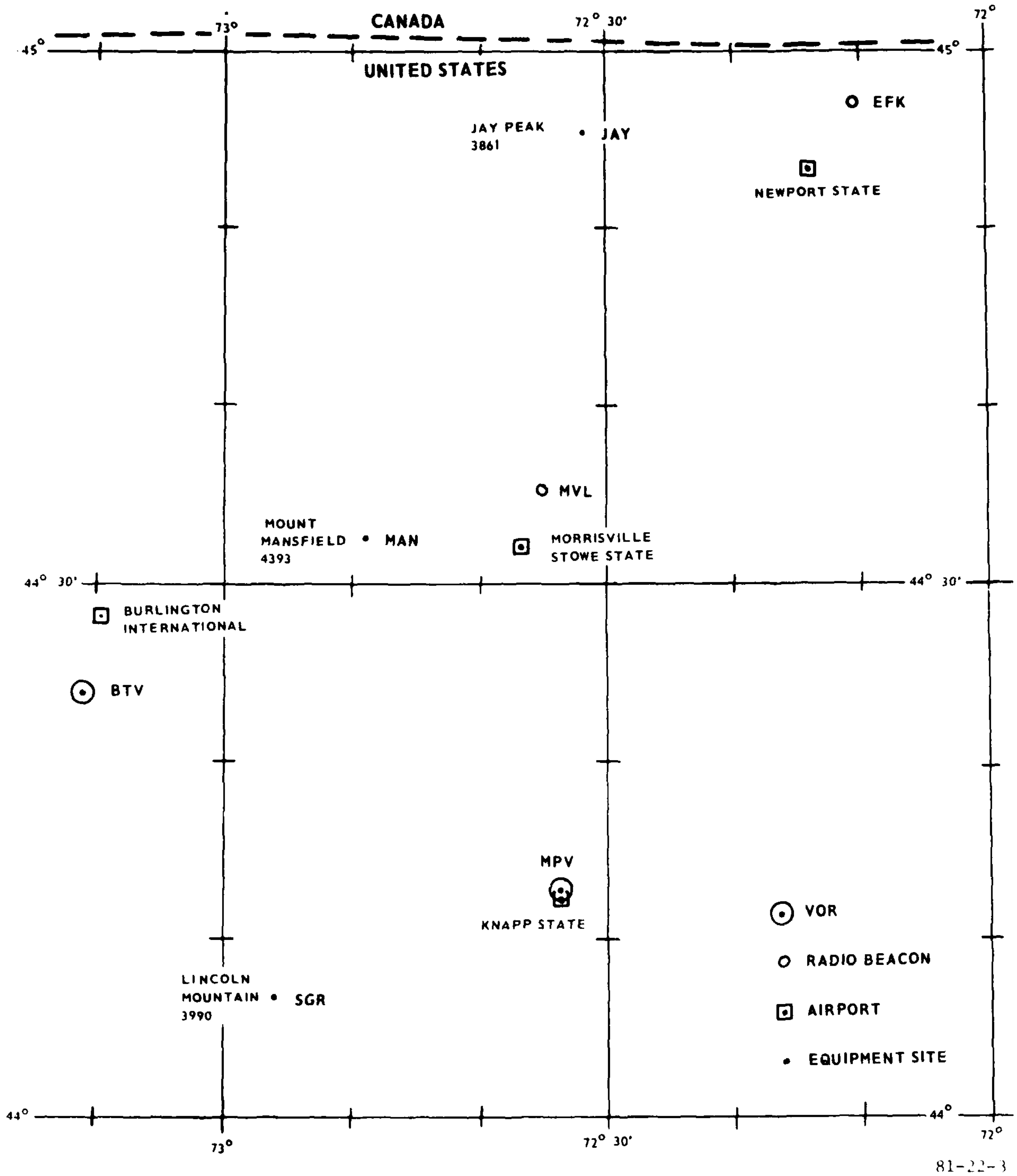

FIGURE 3. TEST AIRPORTS AND BUTLER DME SITES

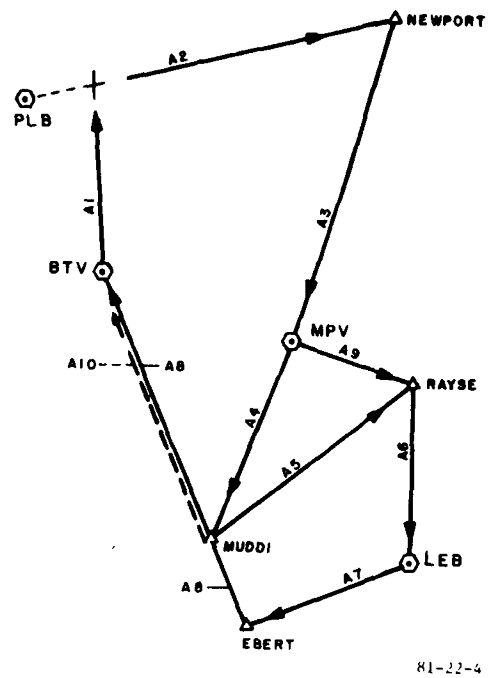

FIGURE 4. EN ROUTE PATTERN A

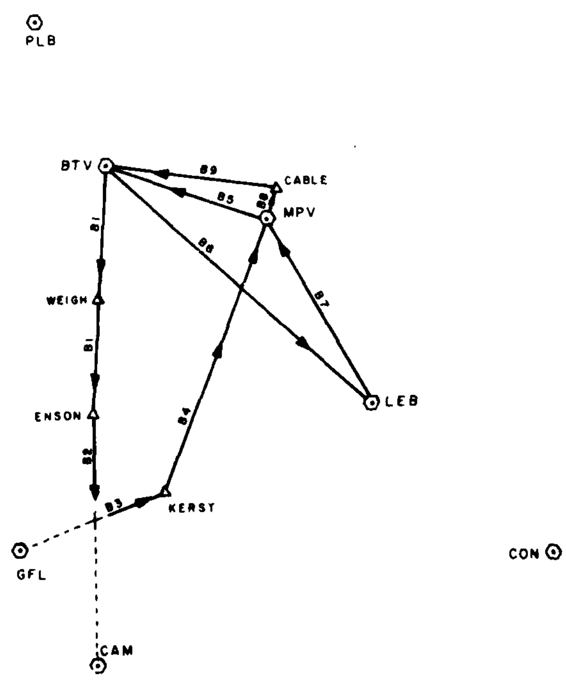

FIGURE 5. EN ROUTE PATTERN B

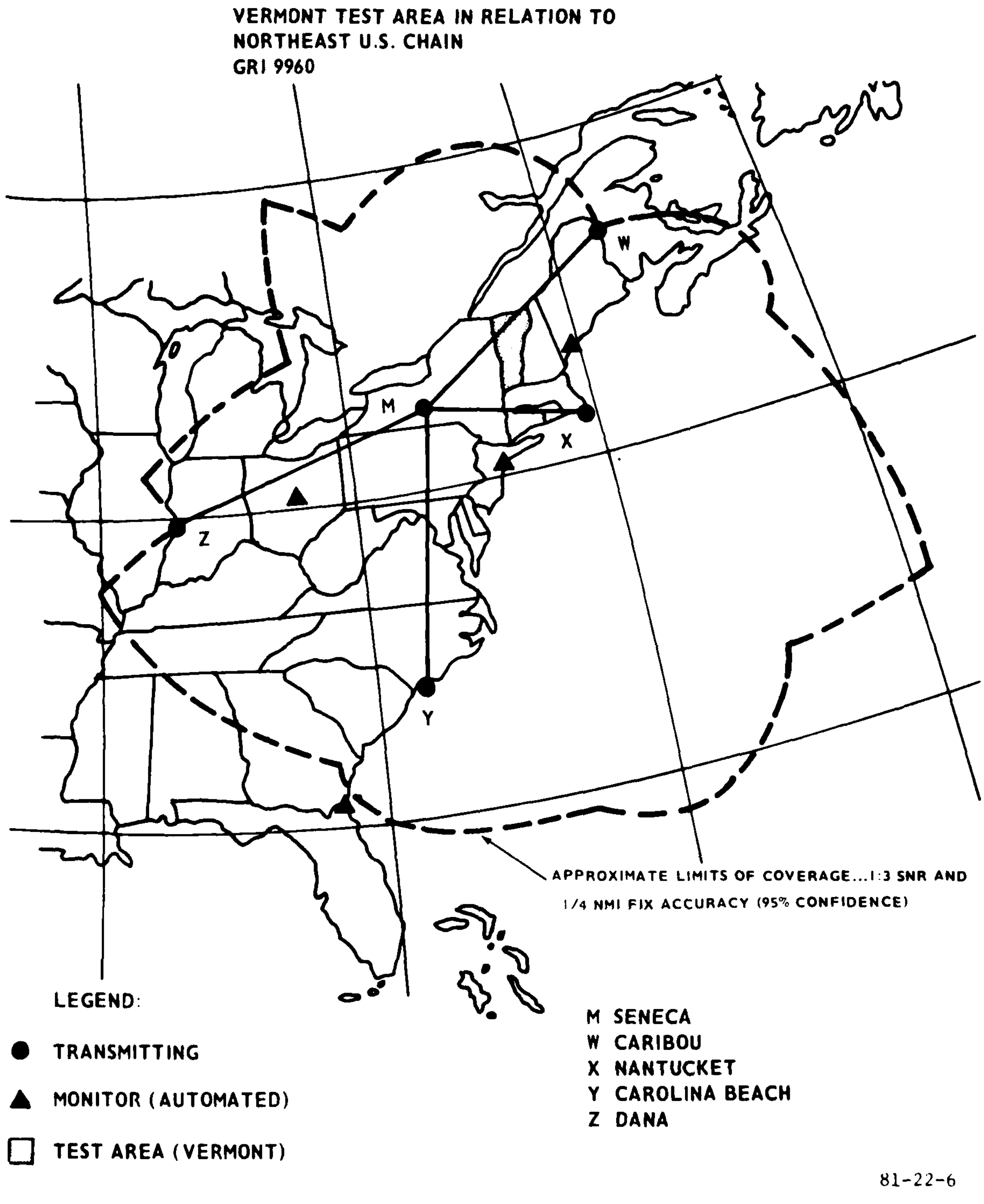

FIGURE 6. VERMONT TEST AREA IN RELATION TO LORAN-C 9960 CHAIN

TABLE 3. VERMONT TEST PROFILE CV-580; RAPPS 1; TDL-711

Nonprecision Approaches

Runway	Date	Triad	Runs	Runway	Date	Triad	Runs
BTV 15	9/27/79	WX	2	MPV 17	10/31/79	WX	4
BTV 15	9/28/79	WX	4	MPV 35	10/31/79	WX	2
BTV 15	10/31/79	WX	2				
BTV 15	11/1/79	WX	2	EFK 36	3/6/80	WX	1
BTV 15	11/1/79	XY	1				
BTV 01	11/1/79	WX	4	MLV 19	3/6/80	WX	2

En Route Flights

Date	MSL Altitude (ft)	Day/Night	Triad	Route	Hours
9/26/79	10,500	Day	WX	A, B	1.5
9/26/79	10,500	Night	WX	A, B	2.0
9/28/79	4,500 - 6,500	Day	WX	A, B	1.7
11/1/79	4,500 - 6,500	Day	WX	A, B	1.5
3/7/80	8,000	Day	WX	A	1.0

NOTE: WX triad = Seneca, Caribou, Nantucket
XY triad = Seneca, Nantucket, Carolina Beach
BTV = Burlington, Vt.
MPV = Montpelier, Vt.
EFK = Newport, Vt.
MLV = Morrisville, Vt.

7. Stores necessary information in a permanent file for subsequent data plots and for compilation of error statistics.

RESTRICTIONS ON AVAILABLE DATA. If fitted ranges for only two of the six DME stations were available (due to line-of-sight limitations on the stations or zero range reading during station identification), the fitted range was not entered into the position computing algorithm. Succeeding sets of fitted ranges were examined until the required three or more DME stations were available. In addition, the position computing algorithm required entry of an initial position, with convergence to the correct position requiring approximately six computations. Consequently, data gaps in RAPPS position occurred occasionally.

RAPPS had a very slow data rate of 6 seconds per data block. This factor, coupled with DME signal loss during turns when the antenna was shielded by the aircraft, meant that RAPPS could not provide a reliable position solution in turns. Therefore, statistical calculations were restricted to straight line segments of en route flights.

Due to design limitations of the RAPPS data collection subsystem, only a crosstrack deviation indicator from the TDL-711 was available to the pilot. Waypoints and leg changes were entered on the control display unit by the project engineer at the RAPPS rack located in the passenger area of the CV-580. Under these conditions, computation of flight technical error (FTE) would not be a valid representation of this parameter. Consequently, only the airborne equipment error (i.e., the difference between the LORAN-C and the RAPPS-computed position) entered into the statistical computations for comparison with AC 90-45A. This equipment error was resolved into crosstrack (CTE) and along-track (ATE) components. The AC 90-45A requirements call for 2-sigma (95 percent probability) values of 0.33 nmi for CTE and 0.30 nmi for ATE during nonprecision approaches, and 1.5 nmi for both CTE and ATE during en route flights.

Although TDL-424 latitude/longitude were recorded by RAPPS, the absence of additional parameters (i.e., signal quality number, envelope number, etc.) precluded an adequate evaluation of this system. The comparison of TDL-424 error statistics with AC 90-45A requirements was not considered appropriate because supplemental information was not available for data editing.

RESULTS

Fourteen hours of usable LORAN-C/RAPPS data, 7 hours en route, and 7 hours nonprecision approaches, have been collected in the CV-580 during the Vermont Phase I tests. Accuracy statistics have been calculated for these flights. Ground checks of the equipment at surveyed calibration points provide comparisons of actual values with LORAN-C latitude, longitude, and TD's. Tests at Rutland Airport were aborted due to inoperative portable DME's. The TDL-424 data were inadequate for proper evaluation of this system because of restrictions imposed by the RAPPS' data recording design; only latitude/longitude could be recorded.

Baseline data, consisting of TDL-711 TD's and corresponding RAPPS position locations, have been collected from 14 hours of Vermont flights (en route and approach). These data will be used by the FAA Technical Center in work with a dynamic LORAN-C simulator and for comparison with flights made with a low-cost LORAN-C receiver (currently under design by contractor).

ACCURACY STATISTICS.

Based upon the accuracy analysis described in reference 5 (RAPPS versus

Nike/Hercules Radar Tracking System), the RAPPS I may be characterized as a 0.08 nmi (2-sigma) position measurement system. Since AC 90-45A requires nonprecision accuracy criteria of 0.33 nmi (2-sigma) for crosstrack error of the airborne equipment and 0.30 nmi (2-sigma) for along track error, the resultant radial error is 0.45 nmi (2-sigma). Thus, RAPPS I provides a measurement tool which is approximately five times as accurate as the required criteria for approaches.

Error statistics for each flight segment were generated for comparison with AC 90-45A. The 2-sigma values for CTE and ATE from all flights were examined. TDL-711 data with WX triad are summarized in table 4. This tabulation includes the flight identification (airport identifier and runway number for approaches, A or B flight segment identifier for en route); the number of runs made for the given segment; and the maximum values (2-sigma) for CTE and ATE from the set of such values obtained for these runs. The FAA requirements (listed in the line marked AC 90-45A in table 4) were satisfied for each of the nonprecision approaches at the four airports. For en route flights, the AC 90-45A requirements were satisfied for all but two of the segments.

The exceptions (marked by double asterisks in table 4) occurred during a flight when the TDL-711 switched secondaries as a result of low signal quality number for the Nantucket signal during the turn from one flight leg to the next. Because of a slow time constant in this early version of the software, erroneous latitude/longitude values (in the along-track direction) were displayed while the algorithm converged. When the Nantucket signal was adequate, the TDL-711 switched back to the original triad, again producing erroneous latitude/longitude values while the algorithm converged. For each triad switch, about 12 seconds was required before a stable position value was produced. The erroneous latitude/longitude values were included in the statistics and resulted in the large error values. It should be noted that during the algorithm convergence operation, the TDL-711 TD's remained consistent with a correct position as compared to a TD contour chart, but the displayed values of latitude/longitude distance to waypoint, ground speed, and crosstrack deviation indicator became unreliable.

The value of 1.25 nmi for ATE, marked by a single asterisk in table 4 for en route segment B3, resulted when both Caribou and Carolina Beach signal quality numbers dropped below threshold for about 45 seconds after the steep turn from the preceding flight leg. Since the TDL-711 software had been modified so that the algorithm converged more quickly, the errors did not exceed the AC 90-45A requirements.

The ranges of 2-sigma error values obtained for en route flights at both medium and low altitudes, day and night, were comparable; no significant differences could be detected.

NORTHING AND EASTING ERRORS.

By examining northing and easting errors (i.e., the north and east components of the position difference between LORAN-C and an independent reference system) a measure of LORAN-C grid bias was obtained. Table 5 lists the range of the mean values for the TDL-711 northing and easting errors (nmi) for the four airports and for the en route flights (combined). Latitude differences between RAPPS position and TDL-711 position provided the northing errors; longitude differences (converted to nmi) produced the easting errors. For the WX triad, approach data at the airports showed a consistent southerly bias error of approximately 0.1 nmi and a westerly bias error of 0.1 nmi or less. The exception was BTV where bias

TABLE 4. ACCURACY STATISTICS

Maximum Values (2-Sigma) for CTE and ATE TDL-711; 9960 WX Triad

Flight ID	No. of Runs	CTE (nmi)	ATE (nmi)
AC 90-45A	APR	0.33	0.30
BTV 15	10	0.26	0.15
MPV 17	4	0.30	0.20
EFK 36	4	0.15	0.21
BTV 01	4	0.11	0.22
MPV 35	2	0.16	0.24
MVL 19	3	0.23	0.23
AC 90-45A	ENR	1.5	1.5
A1	3	0.13	0.21
A2	5	0.35	0.24
A3	4	0.30	0.25
A4	1	0.24	0.29
A6	1	0.50	0.31
A7	2	0.29	0.15
A8	3	0.34	0.58
A9	1	0.54	0.17
A10	1	0.19	0.12
B1	4	0.24	0.31
B2	4	0.36	0.24
B3	2	1.04	1.25*
B4	4	0.30	0.28
B5	4	0.62	0.35
B6	4	0.86	5.96**
B7	3	0.35	4.94**
B8	2	0.12	0.22
B9	4	0.39	0.33

*Caribou and Carolina Beach signal quality numbers dropped to zero for 45 seconds during steep turn.

**Triad switches from WX to WY; slow time constant in early software produced erroneous latitude/longitude values (in along-track direction) while algorithm converged.

NOTE: APR = Approach
ENR = En Route
WY = Seneca, Caribou, Carolina Beach
BTV = Burlington, Vt.
MPV = Montpelier, Vt.
EFK = Newport, Vt.
MVL = Morrisville, Vt.

TABLE 5. NORTHING AND EASTING ERRORS

Range of Mean Values (nmi) TDL 711; 9960 LORAN-C Chain

Flight Site	Northing	Easting	Triad
BTV	-0.1 to 0.0	-0.1 to 0.1	WX
MPV	-0.2 to -0.1	-0.1 to 0.0	WX
EFK	-0.1	-0.1 to 0.0	WX
MVL	-0.1	-0.1 to 0.0	WX
En Route	-0.5 to 0.0	-0.3 to 0.2	WX
BTV	2.18	0.47	XY

NOTES: Runs with less than 10 data points (1 minute) are excluded. Part of the bias in the approach and en route LORAN-C data is due to the biases in the DME stations used by the RAPPS.

BTV = Burlington, Vt.

MPV = Montpelier, Vt.

EFK = Newport, Vt.

MVL = Morrisville, Vt.

errors included both east and west with magnitude 0.1 nmi or less. En route values for the WX triad also showed a general trend of south and west errors, but the magnitudes were larger. Part of the error magnitude must be attributed to the biases in the DME stations which were used in the RAPPS position solution. Based on the results of the radar tracking tests (reference 5), a nominal 300-foot mean error may be expected with a typical multi-DME system. Furthermore, a rough estimation of the DME biases for the particular configuration used during an en route flight (1 hour) was obtained by comparing each DME range with the position solution given by the remaining set of five DME's. When these estimated biases were removed, the effect on the LORAN-C data was to decrease the mean errors, whereas, the 2-sigma values remained approximately the same. Consequently, the actual LORAN-C bias was probably less than the error indicated. For the single flight made with the XY triad at BTV, the grid bias due to geometry was evident. A northing error of 2.2 nmi and an easting error of 0.5 nmi was measured. Results using area calibration were not available because the RAPPS failed during these specific tests.

Additional corroboration of grid errors was provided by accuracy checks made at surveyed ("1927 North American Datum" converted to "World Geodetic Survey 1972") calibration points at BTV and MPV airports (table 6). Both the TDL-711 and TDL-424 are represented; the WX triad is compared to the XY triad. A south and west bias was evident for the WX triad at BTV for both TDL-711 and TDL-424. At MPV, the TDL-711 indicated no bias, whereas, the TDL-424 showed a north and east bias. The XY triad at BTV showed, roughly, a 1.9 nmi north bias and a 0.5 nmi east bias for both TDL-711 and TDL-424. The bulk of this error was due to the signal from the Y secondary (Carolina Beach) which resulted in a discrepancy of approximately 1.8 microseconds (TDY) from the theoretically predicted value for LORAN-C time difference. The expected position uncertainty for the XY triad at BTV is 700 feet (95 percent confidence). The cause of the additional error could not be determined from the limited data.

CONCLUSIONS

1. The Advisory Circular (AC) 90-45A requirements for TDL-711 equipment errors (i.e., 0.33 nmi crosstrack (CTE) and 0.30 nmi along-track (ATE) 2-sigma values) for nonprecision approaches were met when using the primary LORAN-C triad (WX = Seneca, Caribou, Nantucket) at the four test airports and the Remote Area Precision Positioning System (RAPPS) as a position reference.

2. For the en route segments flown within the State of Vermont, the 2-sigma values for TDL-711 equipment errors were significantly smaller (0.6 nautical mile (nmi) maximum) than the AC 90-45A requirements (1.5 nmi) when the primary triad (WX) was used and when no automatic triad switches occurred during the flight.

3. Even though revised software in the TDL-711 reduced the problem of large position errors when triad switches occured in turns, accuracy requirements might be exceeded if an automatic triad switch occurred during a procedural maneuver within the terminal area where AC 90-45A requirements are stringent.

4. The erroneous navigation values of the TDL-711, which were displayed during the position convergence operation of the latitude/longitude conversion algorithm following a triad switch, may be disorienting to a general aviation pilot and decrease his confidence in the equipment.

TABLE 6. ACCURACY CHECK AT CALIBRATION POINTS

Range of LAT, LON, TD'S 9960 LORAN-C Chain

LORAN/Triad	No. of Readings	ΔLAT Min.	ΔLAT Max.	ΔLONG Min.	ΔLONG Max.	ΔTDW Min.	ΔTDW Max.	ΔTDX Min.	ΔTDX Max.	ΔTDY Min.	ΔTDY Max.	Location
TDL-711/WX	8	-0.1	0.0	0.0	0.0	-0.17	+0.43	-0.11	-0.01			BTV CAL PT
TDL-424/WX	5	-0.03	0.00	-0.05	-0.01	-0.12	+0.17	-0.10	+0.08			BTV CAL PT
TDL-711/XY	1		+1.9		+0.50		-0.31				-1.82	BTV CAL PT
TDL-424/XY	3	+1.91	+2.00	+0.45	+0.51	-0.07	+0.07			+1.97	+1.79	BTV CAL PT
TDL-711/WX	4		0.0		0.0	0.00	+0.50	0.00	+0.30			MPV
TDL-424/WX	2	+0.06	+0.06	+0.04	+0.05	+0.35	+0.37	-0.04	+0.24			MPV

ΔLAT (Minutes) = LAT (LORAN-C) -LAT (Reference Point)
ΔLON (Minutes) = LON (Reference Point) -LON (LORAN-C)
Positive LAT = Northing error
Positive LONG = Easting error
ΔTDi (μs) = TD (Reference Point) -TD (LORAN-C)
CAL PT = Calibration Point Surveyed for LORAN-C Tests
BTV = Burlington, Vt.
MPV = Montpelier, Vt.

5. The grid bias for the primary WX triad (i.e., Seneca, Caribou, Nantucket), evident from both flight and ground check data at the test airports, was too small (e.g., generally 0.1 nmi or less to the south and to the west) to require area calibration prior to flights. The bias for the XY triad (Seneca, Nantucket, Carolina Beach), on the other hand, was significant (approximately 1.9 nmi north and 0.5 nmi east). However, tests using area calibration were invalidated because the RAPPS was inoperative.

6. With RAPPS as position reference, no significant differences in error statistics could be detected for en route flights at medium versus low altitude or for day versus night.

RECOMMENDATIONS

1. Future flight tests with the TDL-711 long range navigation (LORAN)-C Navigator should include a study of recovery time of the latitude/longitude solution after automatic triad switch caused by signal dropout during a turn. Tests should be conducted on the tracking range at the Federal Aviation Administration (FAA) Technical Center to determine this recovery time as a function of bank angle and duration of the turn. Similar tests should also be conducted on en route flights at specific locations where the geometrical dilution of precision (GDOP), which is a function of the crossing angles of the LORAN-C lines of position (LOP), is slight, moderate, and major (baseline extension).

2. In view of the significant latitude/longitude biases which are possible when an alternate triad, rather than the primary triad, must be used, future flight tests should address the effect of inflight triad switch on accuracy statistics and on pilot performance.

3. The effect of area calibration, which aligns the LORAN-C grid with the known latitude/longitude, should also be investigated to determine the boundaries of the area beyond which the calibration may increase the position errors rather than decrease them. If mountainous terrain causes significant localized LORAN-C grid distortion at a particular airport, then the zone of effectiveness for an area calibration entered at this airport is expected to be small.

REFERENCES

1. Hefley, G., The Development of LORAN-C Navigation and Timing, NBS Monograph 129, October 1972.

2. Hoffman, W. C., Test Procedures for Flight Evaluation of LORAN-C in the State of Vermont, Transportation Systems Center, Report No. RS914-PM-79-29, December 1979.

3. Scalise, T. E., Bolz, E. H., and McConkey, E. D., West Coast LORAN-C Flight Test, Federal Aviation Administration, Report No. FAA-RD-80-28, March 1980.

4. Sierra Nevada Corporation and AMEX Systems, Inc., Remote Area Precision Positioning System: Phase I, Contract No. DOT-FA78WAI-955, December 1979.

5. Cheung, S., and Polillo, R., Data Reduction and Analysis Techniques Used in Determining the Accuracy of the Remote Airborne Precision Positioning System (RAPPS), Federal Aviation Administration, Report No. NA-80-32-LR, February 1980.

6. Naimo, M., T & E of Remote Area Precision Positioning System (RAPPS), Phase I, Federal Aviation Administration, Report FAA-CT-80-52, March 1981.